The Power and On-Board Propulsion Technology Division

Sheila Bailey
216-433-2224

Sheila.Bailey@lerc.nasa.gov

National Aeronautics and Space Administration
Lewis Research Center

LeRC INVOLVEMENT IN NATIONAL POWER & ON-BOARD PROPULSION TECHNOLOGY PROGRAMS FY 96

POWER & ON-BOARD PROPULSION TECHNOLOGY DIVISION

NASA

OSAT
- SPACECRAFT & REMOTE SENSING
- CLEAN CAR (PNGV)
- CCDS/INSTITUTES
  - AUBURN
  - TEXAS A&M

ISSA
- PV ARRAYS
- BATTERIES
- SPACE ENVIRONMENT
- EPS TESTBED
- RADIATORS

CODES M, S, U
- EMA's AND INTEGRATED ELECTRICAL PWR. SYS.
- NEW MILLENNIUM (DS-1, EO-1)
- SPACE ENVIRONMENT
- HST, RF
- FUEL CELLS, PMAD

CODE AE
- BATTERIES
- WIRING
- ENVIRONMENT
- SYS. ENGINEERING

NASA

AERONAUTICS
- FBL/POWER-BY-WIRE
- ERAST
- RBCC

DOE
- FUEL CELLS
- BATTERIES
- PV's
- DYNAMIC SYSTEMS
- HYBRID VEHICLES
- SBIR's
- PLASMA PROCESSING & MANUFACTURING

ARPA
- BATTERIES
- UUV, FUEL CELLS
- SEMI-CONDUCTORS
- COATINGS
- TRP's

NRL
- SOLAR DYNAMICS
- UAV
- HALL THRUSTERS
- DIRECT DRIVE SYSTEM
- ARCJET & ION

USAF
- PV's/BATTERIES
- THERMAL MGMT./HEAT PIPES
- MORE ELECT. AIRPLANE
- EMA's
- UAV
- RADIATORS
- SOLAR BI-MODAL/IBUS
- FLYWHEELS
- HALL THRUSTERS, PPT, ADV. BIPROPS

BMDO
- SPACE ENVIRONMENT
- INNOVATIVE TECH
- POWER/PROPULSION AGENT
- HALL THRUSTERS
- SCARLET
- LOW THRUST CHEMICALS

NSF / NIST
- ANTARCTIC POWER
- SENSORS
- ATP

PNGV
- SYSTEMS ANALYSIS
- BATTERIES
- FUEL CELLS
- PMAD
- CONVERSION
- TEST BEDS

FLIGHT EXPERIMENTS
- APEX / LDEF
- PASP +
- COMET
- MESUR/PATHFINDER ROVER
- NSTAR
- MIGHTY SAT II.1
- NaS
- TES, SAMPIE 1, 2
- TRMM/EOS
- EURECA
- PFF
- SSTI
- NEW MILLENNIUM (DS-1, EO-1)

U. S. NAVY
- ELECTROLYZERS
- RFC TEST BED

CIA
- BATTERIES
- FUEL CELLS

OTHERS
- > 128 JOINT/CO-OPERATIVE PROGRAMS
  - INDUSTRIES
  - GOVERNMENT
  - UNIVERSITIES
  - ETC.

LeRC SPACECRAFT - SYSTEM POWER TECHNOLOGY PROGRAM

PRESENT MAJOR PROGRAM ELEMENTS

*. **28% COMMERCIAL MBG PV MAN TECH PROGRAM**
- 6 x 6 cm COMMERCIAL CELLS - FY 98, 25% AREA, MASS REDUCTION, 15% COST REDUCTION OVER GaAs/Ge
- EOS, COMMERCIAL, DOD, PLANETARY, ISS, HEDS, AERO

*. **2.6 kWe SCARLET CONCENTRATOR ARRAY - FLIGHT HARDWARE FOR NMP FLIGHT**
- ENABLES SEP DEMO, FY 97 FLIGHT HARDWARE TO DEL
- 1.5 SOA IN EFFICIENCY, 30 W/m2 (2 x SOA), 80 W/kg (1.4 x SOA), 1/2 COST
- PLANETARY, DOD, COMMERCIAL, ISS, HEDS

• **ADVANCED CPV Ni-H2 BATTERY**
- > 1 kWe, 100 W-hr/kg 2 x SOA, 60% DOD ~ 2x SOA, 10 YEAR LEO
- EOS, COMMERCIAL, DOD, PLANETERAY, HEDS

• **BIPOLAR NiMH BATTERY - FY 99, < 1 kWe**
- 100 W-hr/kg 3 x SOA, 1/2 VOLUME, 1/2 COST
- EOS, COMMERCIAL, DOD, PLANETARY, ISS, HEDS

*. **FLYWHEEL ENERGY STORAGE/ATTITUDE CONTROL SYSTEM**
- 10 x REDUCTION IN STORAGE SYSTEM W/kg
- 20 Whr/kg DEMO, FY97
- EOS, COMMERCIAL, DOD, SHUTTLE, ISS, TERRESTRIAL, HEDS

*. **MODULAR ELECTRIC POWER SYSTEM BUILDING BLOCKS**
- STANDARDIZED SMALL S/C POWER SYSTEMS
- 400 W/kg, 2 x SOA DEMO FY 96 SSTI FLIGHT, 1000 W/kg - FY 99 COMMERCIAL APPLICATIONS, PLANETARY, EOS, DOD, AERO, HEDS

* LEVERAGED PROGRAM

LeRC SPACECRAFT - SYSTEM POWER TECHNOLOGY PROGRAM

PRESENT MAJOR PROGRAM ELEMENTS
(CONTINUED)

***. 10 - 300 K CRYOGENIC ELECTRONICS SYSTEM FOR PLANETARY SPACECRAFT**

- ELIMINATE RADIOISOTOPE HEATING UNITS,
- EOS

***. LI-SOLID POLYMER - BATTERY**

- 15 A-hr DEMO FY 98
- SPACE PROTOTYPE 00 150 W-hr/kg (3 x SOA)
  250 W-ℓ (3 X SOA)
  1/2 COST, >> 2000 CYCLES
- PLANETARY, GEO, DOD APPLICATIONS, EOS, COMMERCIAL, ISSA, HEDS

***. ADVANCED RADIOISOTOPE POWER SYSTEM DEMONSTRATION**

- 20% EFF., 3 - 5 REDUCTION IN Pu INVENTORY
- FY 98 DEMO, DOWNSELECT - PLANETARY, PLUTO EXPRESS APPLICATION, MARS

* LEVERAGED PROGRAM

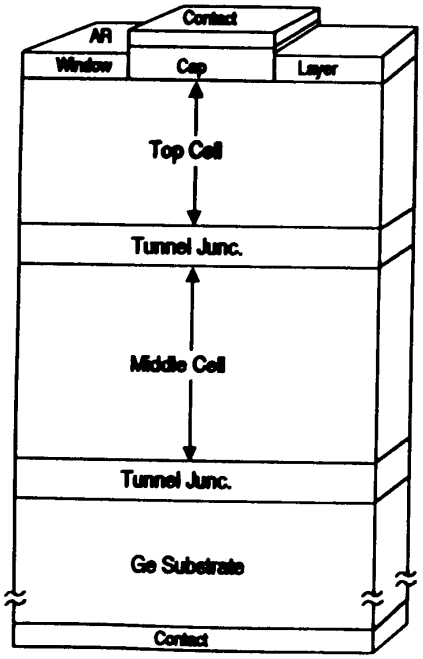
TECHNOLOGY TRENDS

SOLAR CELL TECHNOLOGY

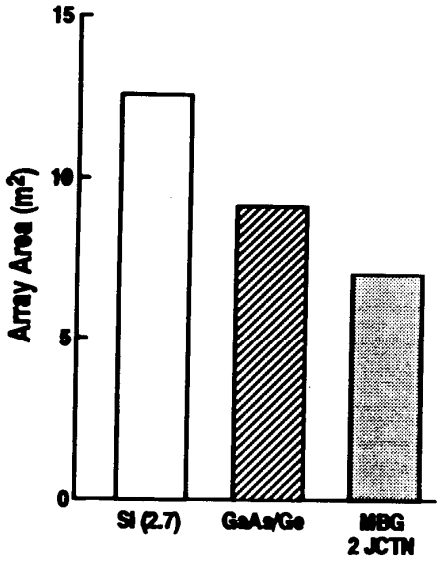
	STATE OF TECHNOLOGIES	NEAR TERM	FUTURE
CRYSTALLINE CELL TECHNOLOGY	Silicon - 14.5% GaAs/(Ge) - 18.5% Production Levels	$GaInP_2$/GaAs - 24% in large area, production $GaInP_2$/GaAs - 26% limited quantities	+ 35% CELLS (Planar or Concentrator Applications)
THIN FILM CELL TECHNOLOGY	Not Available	Amorphous - Si - 10%	CIS ~ 20% High efficiency thin film tech., low cost, light weigth, monolithic interconnections, 1000 W/kg
ARRAY TECHNOLOGY	30-50 W/kg - Rigid Panels 60 W/kg - Flexible panels Cost ~ $ 1000 - $ 2000/W	APSA - 130 W/kg (Si), 5.3 kW GEO Ultraflex - 115 W/kg (Si), 140 W/kg (GaAs) both mission and size specified/limited SCARLET concentrator - 50 - 60 W/kg radiation hardness, low cost $500 - $700/W	Lightweight array structures (inflatables, shaped memory mech., hybrid designs) Goal: 300 W/kg @ array level, < 300 $/W High voltage array designs, 300-1000V reduce/eliminate PMAD, direct drive EP Large area concentrators/dense arrays Synergistic SC subsystems, combine power & communications, power and propulsion at the SC level Integrated energy conversion/power storage concepts

PHOTOVOLTAICS

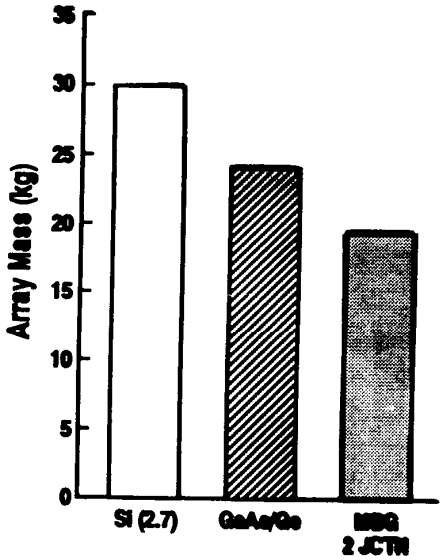
- **THE NEXT STEP IN IMPROVED EFFICIENCY, AT COMPETITIVE COST**
  - **PLANAR MULTI-BAND GAP CELLS/ARRAYS**
    - NEAR TERM LARGE AREA (6 x 6 cm) CELLS, 24-26% EFFICIENT
    - GaInP/GaAs
  - **WIDE RANGE OF APPLICATIONS, NASA, DOD, COMMERCIAL**
  - **COMMERCIAL CELLS IN 1998**



MBG Cell Cross Section



Array Cell Type
Array Area for Different Cells *



Array Cell Type
Array Mass for Different Cells *

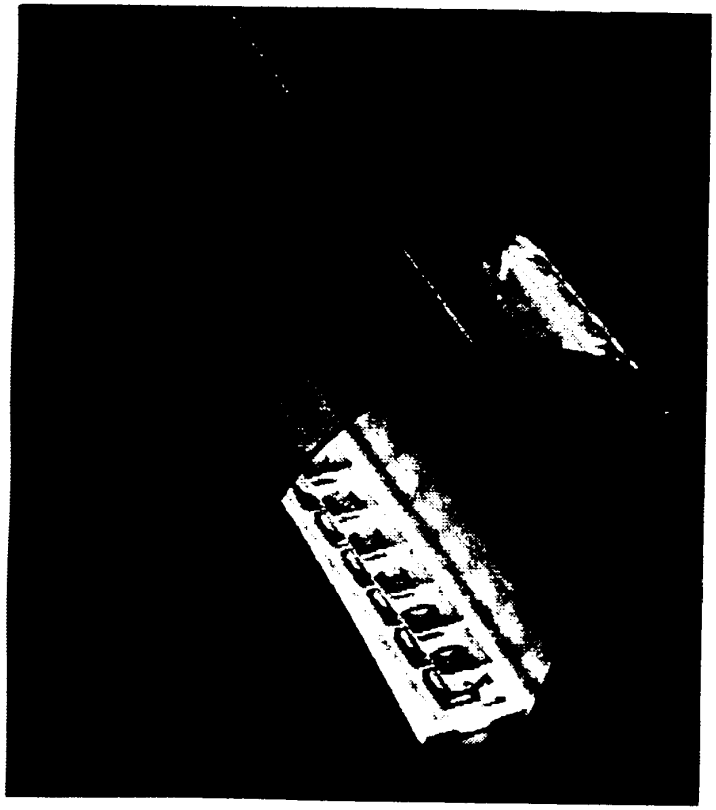
*** 1.5 kW ARRAY**

PHOTOVOLTAICS

- **ADVANCED RESEARCH MULTI-BAND GAP CELLS → ≥ 30 EFFICIENCY**
  - **PLANAR APPLICATIONS**
    - **2 PARALLEL APPROACHES**
      - 3 JUNCTION CELLS $GaInP_2$/GaAs/Ge
        - COMPLEX STRUCTURE
        - FAMILIAR MATERIALS
      - 2 JUNCTION CELLS FROM ALTERNATE MATERIALS
        - SIMPLE STRUCTURE
        - MORE COMPLEX MATERIALS
    - **IN-HOUSE SBIR'S**

PHOTOVOLTAICS

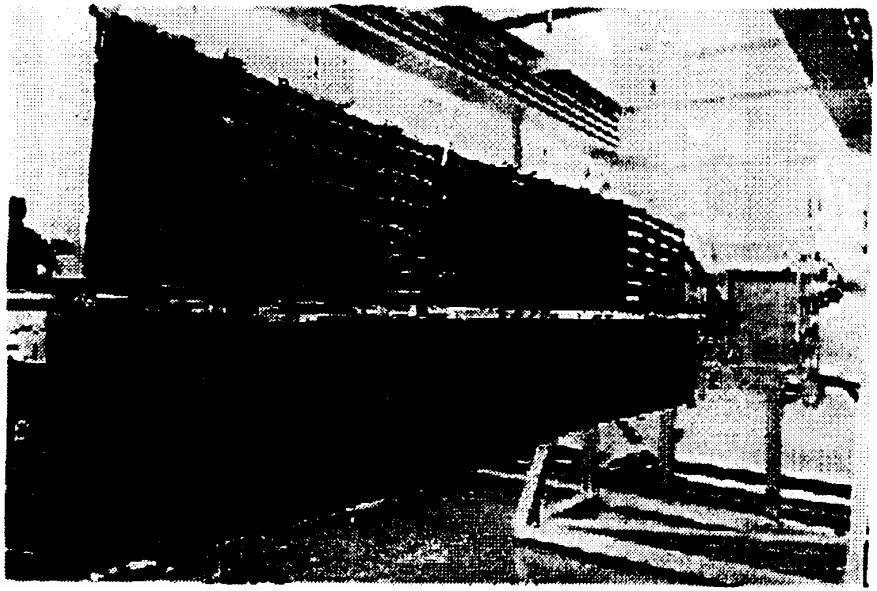
CONCENTRATOR ARRAYS



- NASA STUDIES (EARLY 1980's) SHOWED MULTIPLE BENEFITS
  - LOW COST (< 1/2 CURRENT PLANAR ARRAYS)
    - REDUCED CELL COSTS
    - MANUFACTURING & ASSEMBLY COSTS LOWER BY ~ 50%
  - HIGH PERFORMANCE
    - SMALLER AREA
    - INCREASED RADIATION TOLERANCE
    - HIGH VOLTAGE OPERATION
- LeRC APPROACH: REFRACTIVE, LINEAR CONCENTRATOR OPTICS
  - LOW COST, CURVED FRESNEL LENS @ 7.5x
  - SINGLE AXIS TRACKING
  - SMALL AREA MBG CELL @ 24%

APPLICABLE TO ALL SATELLITE CLASSES/MISSIONS

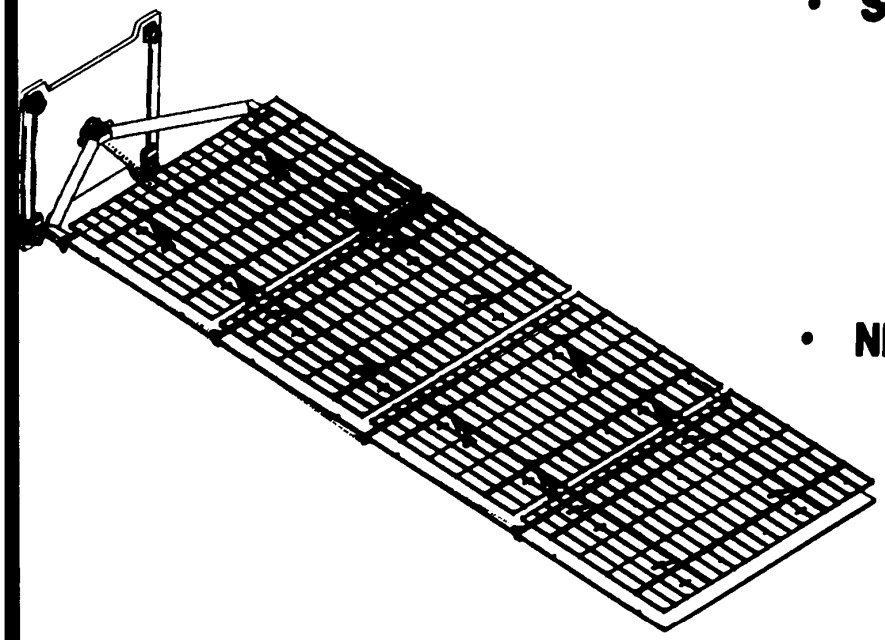
SCARLET Concentrator Array



SCARLET/METEOR ARRAY

- SCARLET (Solar Concentrator Array with Refractive Linear Element Technology) with high efficiency MBG solar cells could provide power for a variety of new missions
- Chosen for solar electric propulsion mission for New Millennium Program- (2.6 kW array)
- Expected major performance advancements
  - Efficiency (1.5 x SOA)
  - Area ~ 300 W/m2 (2.0x SOA)
  - Weight ~ 80 W/kg (1.4 x SOA)
  - Cost ~ 1/2 SOA Planar
  - Radiation hard array
  - Minimum plasma interaction enables high voltage operation
  - Reduces low illumination, low temperature (LILT) effects

PHOTOVOLTAICS
SCARLET II



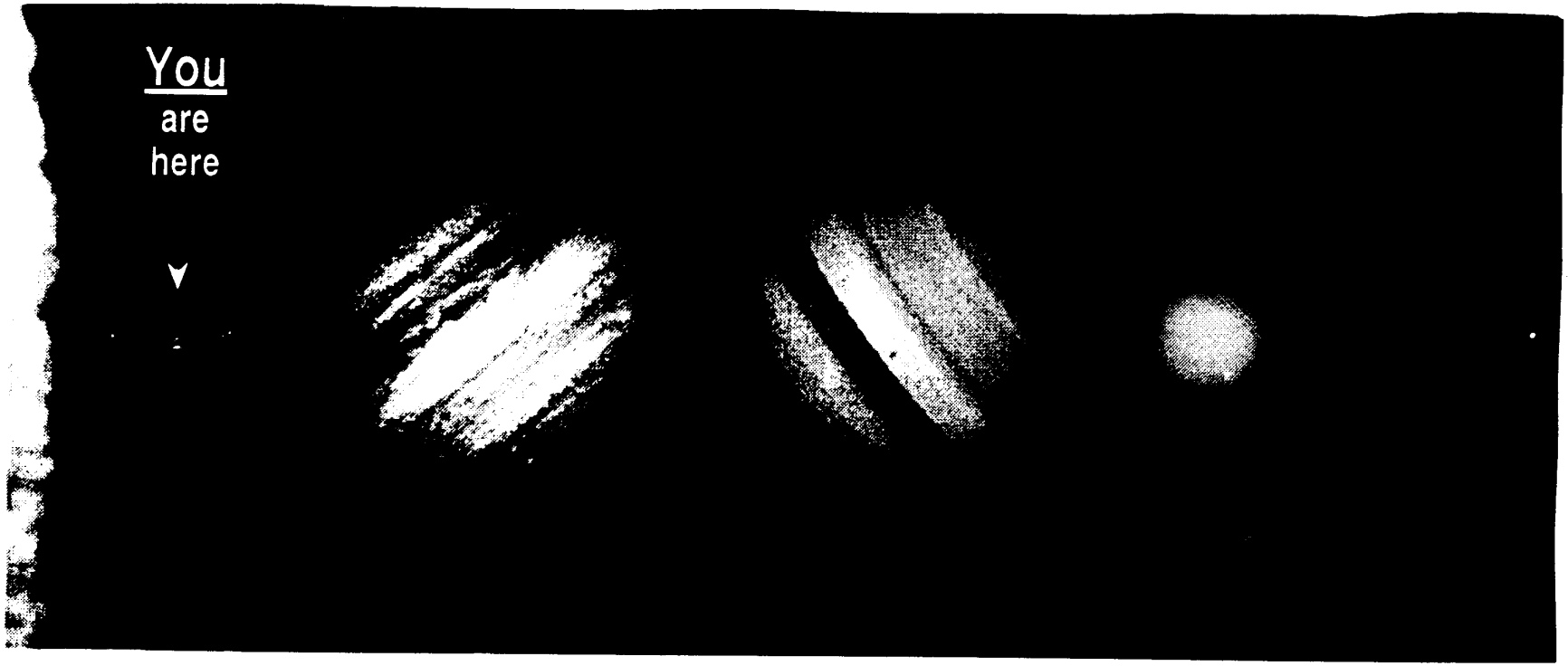
SCARLET II / DS-1 WING

- SCARLET PV CONCENTRATOR TECHNOLOGY
  - BASED ON LeRC DEVELOPED TECHNOLOGY (SBIR & BASE PROGRAMS)
  - LeRC PROVIDING TECHNICAL LEADERSHIP AND FACILITIES TO SUPPORT JPL FLIGHT PROGRAM

- NEW MILLENNIUM DS-1 ARRAY
  - FIRST OPERATIONAL USE OF PV CONCENTRATOR TECHNOLOGY IN SPACE
  - STRONG COMMERCIAL INTEREST
  - 2.6 kW ARRAY - GaInP/ GaAs M.J. CELLS
  - POWERS NSTAR ELEC. PROP. SYSTEM
  - AUGUST 1997 DELIVERY, JULY 98 LAUNCH
  - DESIGN EMPHASIZES LOW COST (< 1/2 RECURRING COST vs. SOA)
  - CRITICAL DESIGN REVIEW COMPLETED - JULY 1996

LeRC DEVELOPED TECHNOLOGY TO PROVIDE POWER FOR NMP DEEP SPACE-1 FLIGHT

National Aeronautics and
Space Administration

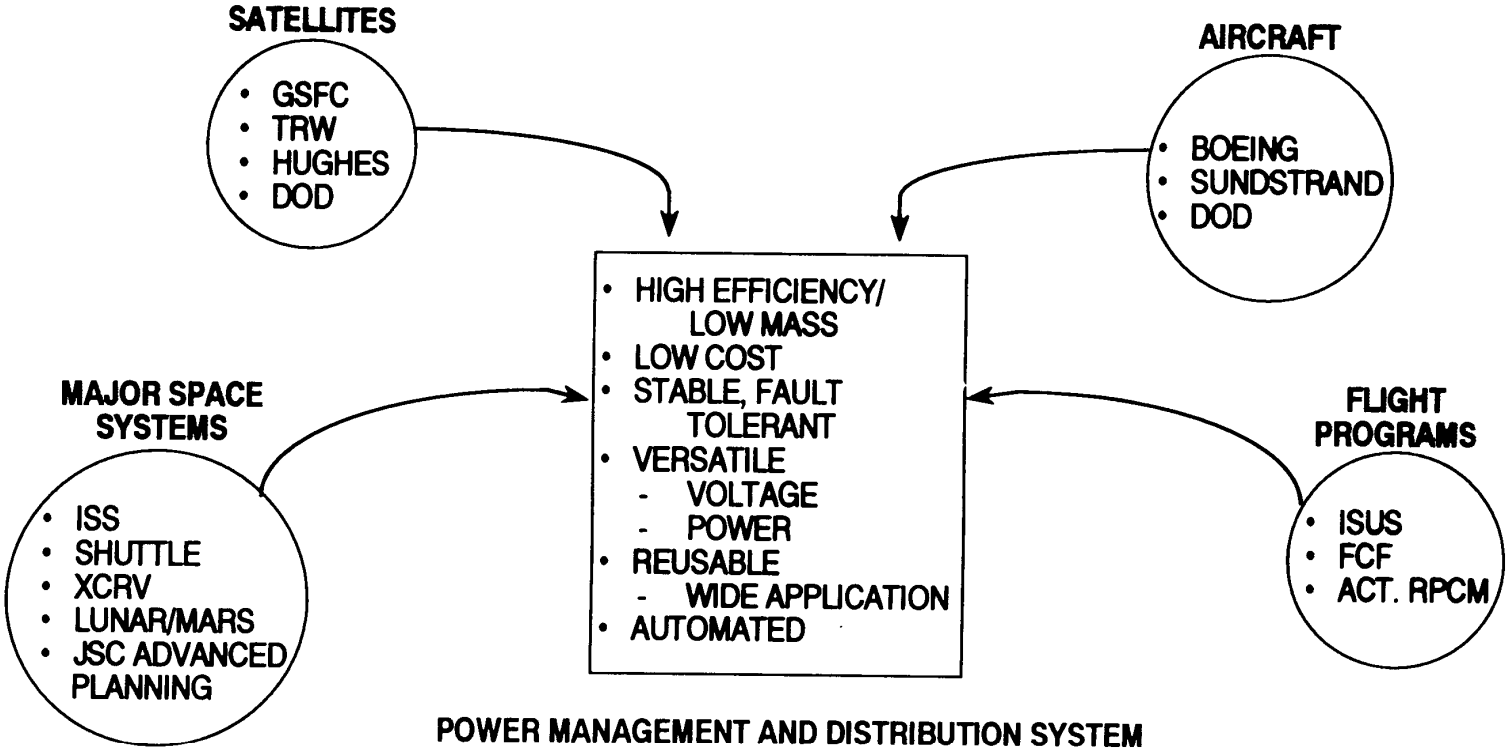


ADVANCED RADIOISOTOPE POWER SYSTEM DEVELOPMENT WITHIN NASA AND DOE

- AMTEC
- THERMOPHOTOVOLTAIC
- STIRLING
- RTG (NOT COVERED)

ELECTRICAL SYSTEMS DEVELOPMENT

LeRC's INVOLVEMENT IN A WIDE RANGE OF PROGRAMS HAS IDENTIFIED A CRITICAL COMMON NEED.



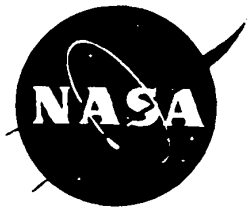
POWER MANAGEMENT AND DISTRIBUTION SYSTEM

RANGE OF PARAMETERS

SWITCHGEAR	-	28V, 120V, 270V
POWER CONVERTERS	-	25 TO 1500 WATTS (SCALEABLE TO 10+ KILOWATTS

ELECTRIC POWER SYSTEM TEST AND INTEGRATION FACILITY

- 35 kW SOLAR ARRAY FIELD AND HIGH VOLTAGE NiH BATTERIES
- SUPPORTS MULTIPLE POWER PROCESSING AND SWITCHING ELEMENTS
- DISTRIBUTED CONTROL & DATA COLLECTION SYSTEM USING 30,000 LINES OF ADA CODE
- RECONFIGURABLE TO SUPPORT A VARIETY OF SYSTEM TOPOLOGIES & APPLICATIONS
- PERFORM SUNLIGHT TO LOAD TESTING OF SPACE ELECTRIC POWER SYSTEMS



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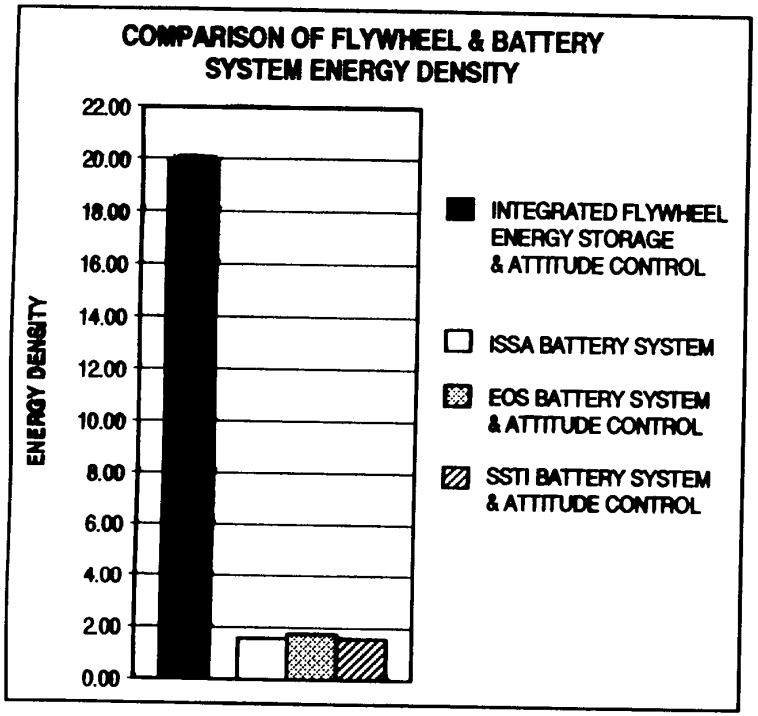
ELECTRONICS FOR COLD OPERATION TEMPERATURES

POWER TECHNOLOGY DIVISION

- **ENABLING TECHNOLOGY FOR NON-NUCLEAR DEEP SPACE MISSIONS (300K ⟶ 40-60K)**
  - IMPROVED SOLID-STATE RELIABILITY
  - REDUCED MASS
  - LOWER COST
- **PROGRAM DEFINED, IMPLEMENTED**
  - SPACECRAFT PAYLOAD INEGRATED POWER REQUIREMENTS
    - ALSO SUPPORTS HIGH DENSITY ELECTRONICS
  - LOW TEMPERATURE COMPONENT CHARACTERIZATION
  - LOW TEMPERATURE SYSTEMS CHARACTERIZATION
  - NEW COMPONENT DESIGNS

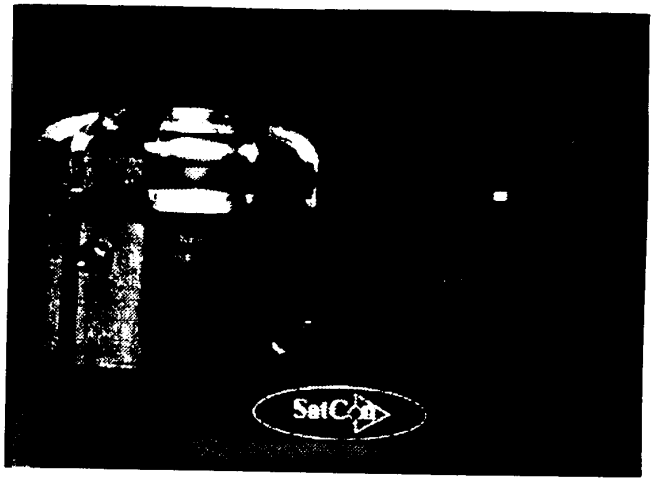
FLYWHEEL ENERGY STORAGE SYSTEMS

- **BENEFIT OF FLYWHEEL ENERGY STORAGE OVER SOA BATTERY SYSTEMS CLEARLY IDENTIFIED**



- 10 TO 20 X IN W-Hr/lb IMPROVEMENT ATTAINABLE
- ISS ACKNOWLEDGES BENEFIT OF FLYWHEEL SYSTEM AS REPLACEMENT FOR NiH_2 BATTERIES

- **BATTERY SYSTEMS**
  - **BATTERY: CELL + WIRE INTERCONNECTS, BYPASS DIODES, SUPPORT BOX**
  - **BATTERY SYSTEM: RECONDITIONING CIRCUITS, ARRAY REGULATOR, ARRAY OVERSIZE, BUS REGULATOR**



TECHNOLOGY TRENDS
BATTERIES

POWER TECHN DIVI

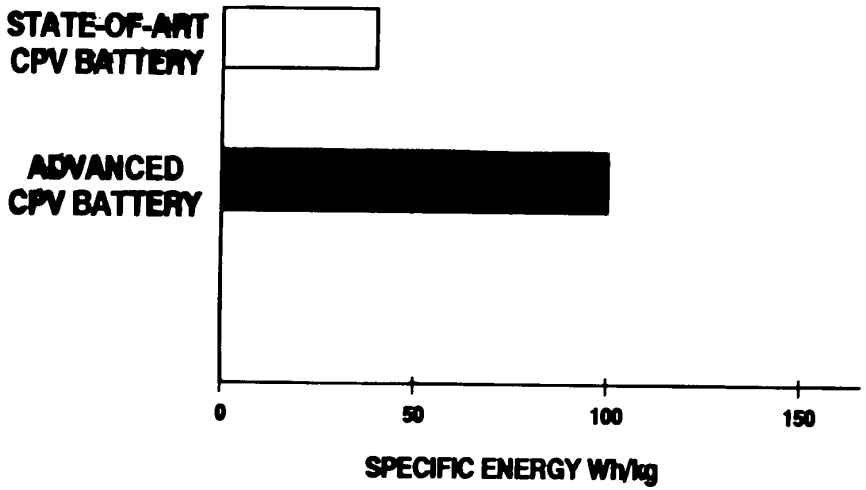
STATE OF TECHNOLOGY		NEAR TERM	FUTURE
		COMMERCIAL APPLICATIONS	LIGHTWEIGHT Ni ELECTRODE
*CELL Wh/kg	50	80	100
BATTERY Wh/kg	32	50	65
Wh/l	17	20	20
RELATIVE COST	1	.8	.6
LIFE (YRS)	6	8	10 LEO
		COMMERCIAL APPLICATIONS	LIGHTWEIGHT Ni ELECTRODES OPTIMIZED DESIGN FEATURES
CELL Wh/kg	55	70	120
BATTERY Wh/kg	45	55	100
Wh/l	60	80	120
RELATIVE COST	1	.5	.5
LIFE (YRS)	2	5	10 LEO
		PRISMATIC	LIGHTWEIGHT Ni ELECTRODES BIPOLAR DESIGN
CELL Wh/kg	55	65	100
BATTERY Wh/kg	53	50	80
Wh/l	160	185	260
RELATIVE COST	1	.6	.5
LIFE (YRS)	1	5	20 GEO
		OPTIMIZED INTERCALATION	ALL SOLID MULTI LAYER DESIGN
CELL Wh/kg	160	180	220
BATTERY Wh/kg	130	150	175
Wh/l	240	260	300
RELATIVE COST	1	.5	.2
LIFE (YRS)	.3	10	20 GEO

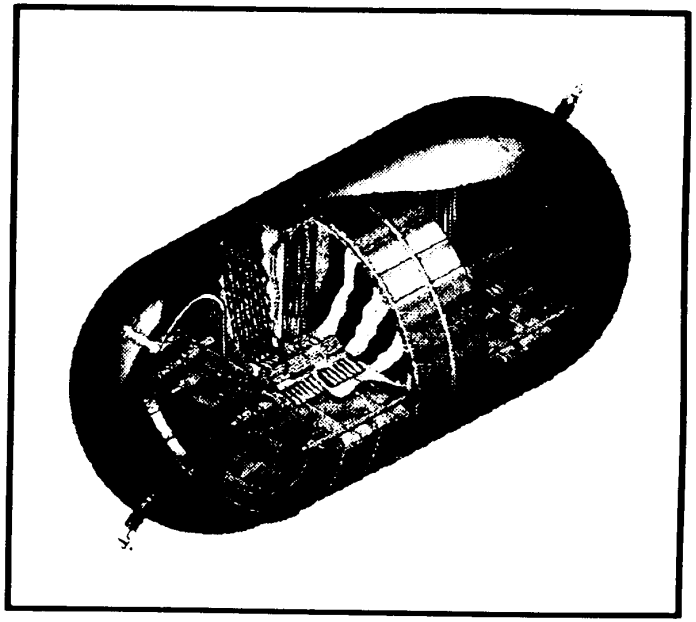
@ 100% DOD, BATTERY NUMBERS @ 80% DOD

LeRC LITHIUM ION SOLID POLYMER BATTERY PROGRAM ELEMENTS

- **MAJOR EFFORT TO DEVELOP A DUAL-USE Li-ION SOLID POLYMER BATTERY FOR COMMERCIAL, MILITARY, & SPACE APPLICATIONS**
  - DEMONSTRATED 3 x IMPROVEMENT IN W-hr/kg OVER NiCd
  - AUTOMATED PRODUCTION
- **LeRC RESEARCH & TECHNOLOGY EFFORTS TO IMPROVE BATTERY PERFORMANCE AND LIFE TO MEET SPACE APPLICATION REQUIREMENTS**
  - LeRC/TEXAS A&M/HUGHES FUNDAMENTAL INVESTIGATIONS
    - **ADDRESSING LI-ION POLYMER CELL FUNDAMENTALS**
  - LeRC IN-HOUSE
    - **IMPROVE ANODE PERFORMANCE VIA MODIFICATION OF GRAPHITE STRUCTURE TO INCREASE LI-ION INTERCALATION**
  - LeRC PHASE II SBIR WITH MER, INC.
    - **IMPROVE ANODE PERFORMANCE VIA USE OF SPECIALLY PREPARED SINGLE WALL - OPEN ENDED FULLERENE NANOTUBES**
- **COORDINATION WITH Li-ION BATTERY ASSESSMENT AND CHARACTERIZATION TASKS OF LeRC-MANAGED CODE AE FLIGHT BATTERY SYSTEMS PROGRAM**

ADVANCED LIGHTWEIGHT CPV BATTERY





FEATURES

- 2 x IMPROVEMENT IN SPECIFIC ENERGY - 100 Whr/kg
- 20% VOLUME REDUCTION
- LONG CYCLE LIFE AT DEEP DEPTHS OF DISCHARGE (DOD) - 10 YR LEO AT 60% DOD, 15 YR GEO

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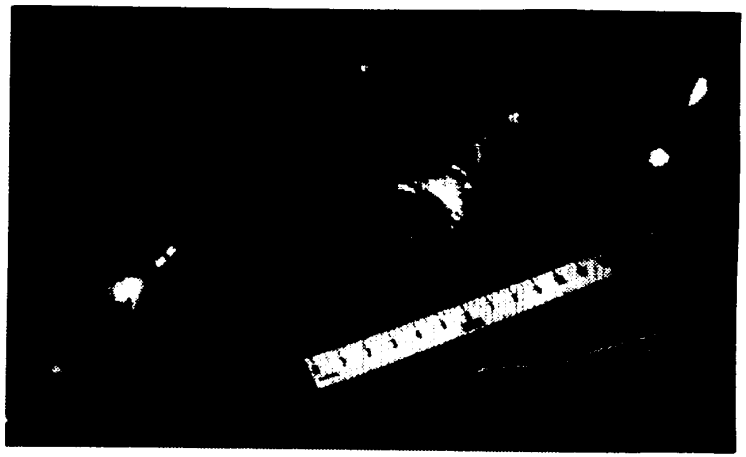
LeRC AWARD WINNING NiH_2 TECHNOLOGY APPLIED TO COMMERCIAL SPACECRAFT AND ISS APPLICATIONS

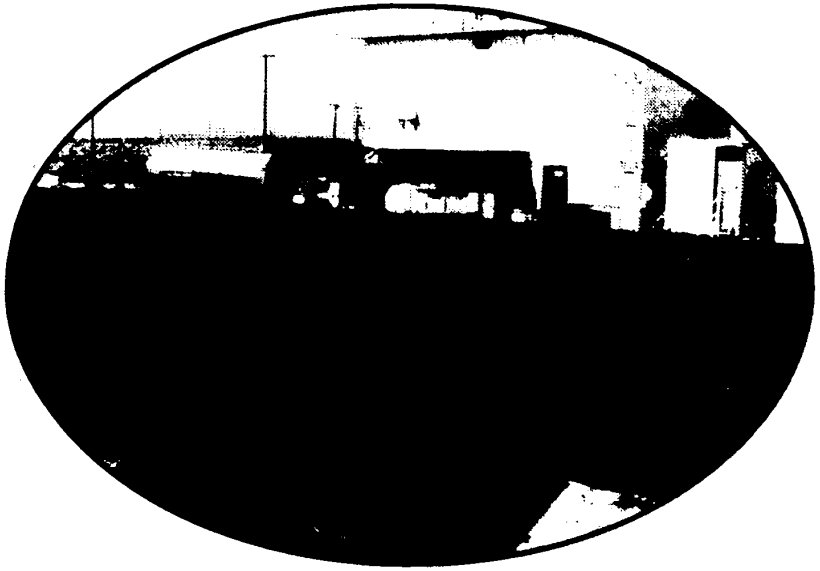
POWER & ON-BOARD PROPULSION TECHNOLOGY DIVISION

- LeRC/HUGHES, IN A COOPERATIVE PROGRAM, HAVE DEVELOPED AN ADVANCED NiH2 BATTERY
  - IMPROVED IPV NICKEL HYDROGEN BATTERIES TO MEET COMMERCIAL SPACECRAFT NEEDS FOR 1997 AND BEYOND
    - 50% VOLUME REDUCTION
    - 20% COST REDUCTION
    - 50% LONGER LIFE
  - CELL DESIGN COMPLETE, FLIGHT BATTERIES BUILT AND BEING FLIGHT QUALIFIED
  - FIRST FLIGHT 1997 - BOOKED ON 26 SPACECRAFT AT PRESENT
  - FURTHER TECHNOLOGY DEVELOPMENT IMPROVEMENT POSSIBLE
    - 5 YEARS ADDITIONAL LIFE
    - 2 x IMPROVEMENT IN W-hr/kg

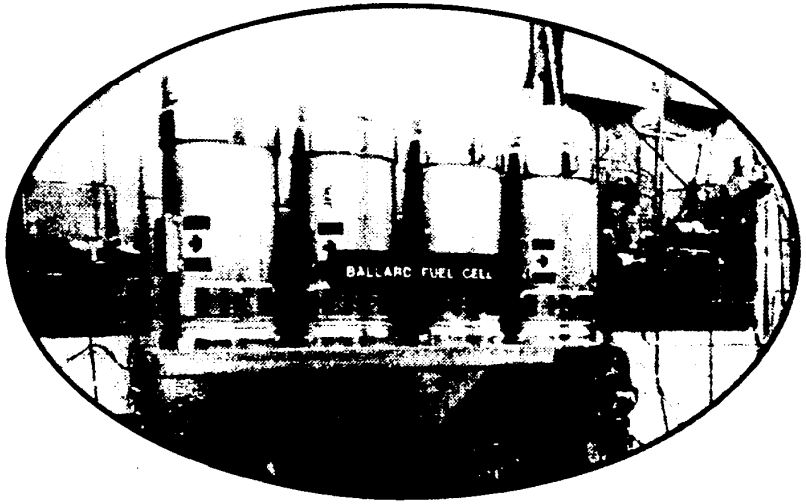


- APPLICATION OF THIS TECHNOLOGY IN IPV BATTERIES COULD BE USED FOR ISS – STUDIES SHOW REDUCTION OF OPERATING COST BY $240 MILLION - AVAILABLE
  - IMPLEMENTATION CURRENTLY BEING CONSIDERED BY CONFIGURATION CONTROL BOARD

LeRC 25 kW SOLAR/REGENERATIVE FUEL TEST BED AT EDWARDS AFB, EDWARDS, CA



Solar Cells



Fuel Cells

Electrolyzer